OBSERVATIONAL STUDY

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Clinical Impact of Standardized Interpretation and Reporting of Multimodality Neuromonitoring Data

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OBJECTIVE: Evaluate the consistency and clinical impact of standardized multimodality neuromonitoring (MNM) interpretation and reporting within a system of care for patients with severe traumatic brain injury (sTBI).

DESIGN: Retrospective, observational historical case-control study.

SETTING: Single-center academic level I trauma center.

INTERVENTIONS: Standardized interpretation of MNM data summarized within daily reports.

MEASUREMENTS MAIN RESULTS: Consecutive patients with sTBI undergoing MNM were included. Historical controls were patients monitored before implementation of standardized MNM interpretation; cases were defined as patients with available MNM interpretative reports. Patient characteristics, physiologic data, and clinical outcomes were recorded, and clinical MNM reporting elements were abstracted. The primary outcome was the Glasgow Outcome Scale score 3–6 months postinjury. One hundred twenty-nine patients were included (age 42 ± 18 yr, 82% men); 45 (35%) patients were monitored before standardized MNM interpretation and reporting, and 84 (65%) patients were monitored after that. Patients undergoing standardized interpretative reporting received fewer hyperosmotic agents (3 [1–6] vs. 6 [1–8]; $p = 0.04$) and spent less time above an intracranial threshold of 22 mm Hg (22% ± 26% vs. 28% ± 24%; $p = 0.05$). The MNM interpretation cohort had a lower proportion of anesthetic days (48% [24–70%] vs. 67% [33–91%]; $p = 0.02$) and higher average end-tidal carbon dioxide during monitoring (34 ± 6 mm Hg vs. 32 ± 6 mm Hg; $p < 0.01$; $d = 0.36$). After controlling for injury severity, patients undergoing standardized MNM interpretation and reporting had an odds of 1.5 (95% CI, 1.37–1.59) for better outcomes.

CONCLUSIONS: Standardized interpretation and reporting of MNM data are a novel approach to provide clinical insight and to guide individualized critical care. In patients with sTBI, independent MNM interpretation and communication to bedside clinical care teams may result in improved intracranial pressure control, fewer medical interventions, and changes in ventilatory management. In this study, the implementation of a system for management, including standardized MNM interpretation, was associated with a significant improvement in outcome.

KEYWORDS: electroencephalography; intracranial pressure; multimodality neuromonitoring; neurocritical care; traumatic brain injury

Multimodality neuromonitoring (MNM) refers to the use of more than one continuous bedside measurement focused on brain mechanics, metabolism, or function used to identify, prevent or treat secondary brain injury (SBI) (1, 2). SBI encompasses brain hypoxia and ischemia, autoregulatory impairment, cerebral edema, intracranial hypertension, metabolic crisis, and seizures or spreading depolarizations (3–5). No single monitoring device

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KEY POINTS

Question: Does implementation of standardized multimodality neuromonitoring (MNM) interpretation and reporting impact clinical care or outcome in patients with severe traumatic brain injury (sTBI)?

Findings: In patients with standardized MNM interpretation and a detailed summary reporting, the authors found less time spent with elevated intracranial pressure, fewer hyperosmotic agents administered, fewer days of anesthetic usage, an increase in average end-tidal carbon dioxide concentrations, and an increase in the odds for a better outcome, compared with patients without standardized interpretation and reporting.

Meaning: Implementing standardized interpretation and reporting of MNM data can impact clinical decision-making and improve the outcome for patients with sTBI.

adequately informs clinicians of pathology across the spectrum of SBI, and there is increasing clinical interest in the use of MNM, which often includes invasive measurements such as intracranial pressure (ICP) and brain tissue oxygen ($Pbto_2$). Less commonly, some centers monitor regional cerebral blood flow (rCBF), cerebral microdialysis (CMD), and electrocorticography (ECOG) from depth or subdural electrodes. These are used in conjunction with standard ICU measures, including arterial blood pressure (ABP), heart rate, and ventilatory parameters such as end-tidal carbon dioxide ($ETco_2$). However, challenges have been identified, including a lack of technology standardization (6) and inadequate time and expertise as barriers to bedside care providers' success in interpreting and acting on MNM information (2), limiting evidence for the clinical benefits of MNM.

In the United States, the most common bedside neuromonitoring device is noninvasive continuous electroencephalography (cEEG), a component of MNM in many institutions (7, 8). cEEG provides an example of a single continuous, data-intensive brain monitor that has been successful in influencing medical decision-making (9, 10), improving hospital length of stay, cost, and clinical outcome (11, 12). This success is in part, the result of standardized terminology that links clinical expertise and consistent cEEG interpretation (13). Usually, cEEG is read, interpreted, and communicated through templated reports by a clinical neurophysiologist independent from the bedside critical care team. This approach has not been implemented for MNM, although some centers have begun to integrate MNM in an analogous way to facilitate the interpretation of this information (14, 15), and there is consensus that clinical reporting may provide added benefit in the use of MNM for clinical care (2). However, there is currently no standard for interpreting MNM data, and the potential impact of implementing a system of clinical management that features independent, interpretive reporting of MNM has not been established (3, 15).

We designed a single-center, retrospective, case-control study to evaluate the impact of standardized MNM interpretation and reporting in the management of patients with severe traumatic brain injury (sTBI). We aimed to compare patients undergoing MNM before and after the implementation of a system of care, including standardized MNM interpretation communicated through daily reports documented within the electronic health record (EHR). We hypothesized that MNM data could be systematically reported and would result in differences in the management of physiologic targets. We further hypothesized that the use of standardized MNM interpretation and reporting would result in improved functional outcomes for 3–6 months.

MATERIAL AND METHODS

Study Design and Cohort Selection

We performed a retrospective, historical case-control cohort study of consecutive sTBI patients requiring MNM admitted from April 2015 to July 2020 to the University of Cincinnati, an American College of Surgeons designated Level I Trauma Center. All patients were admitted to a dedicated neuroscience ICU (NSICU), and care was provided based on national guidelines. The use of MNM was based on a previously published clinical protocol (16). The study was approved by the University of Cincinnati's Internal Review Board (Protocol Title ANIRI-OCD, Approval Number 2015-0654 Effective March 16, 2015) with waiver of informed consent and conducted in accordance with both institutional ethical standards and with the Helsinki Declaration of 1975.

Controls consisted of patients admitted before the implementation of standardized MNM interpretation and reporting in August 2017. Cases were defined as patients with greater than or equal to one clinical MNM interpretive report during monitoring. All patients had a quad-lumen bolt to measure ICP, $Pbto_2$, rCBF, brain temperature and EEG. Patients with less than 12 hours of neuromonitoring were excluded. During the study period, the University of Cincinnati established a Neurotrauma Center and joint institutional clinical management guidelines were updated in January 2017.

MNM Interpretation and Reporting

Interpretation and reporting were performed as part of clinical care by a single board-certified neurointensivist and clinical neurophysiologist (B.F.) using a data aggregation platform and data visualization software (CNS Envision, Natus Medical Incorporated; Middleton, WI). Reports were generated daily from the beginning of monitoring until MNM was discontinued. Reporting was documented in a templated note, including sections describing the following MNM measurements: ICP, cerebral perfusion pressure (CPP), autoregulatory indices, $Pbto_2$, $ETco_2$, rCBF, brain and core temperature, CMD, cEEG, ECOG, and pupillometry. Bedside annotations by clinical care providers at the time of care and EHR data were used to correlate clinical context with MNM information. Daily reports were placed within the EHR at the beginning of NSICU rounds. Treatment decisions were made by the clinical care team.

Data Collection

Clinical information was abstracted from the EHR, including data to calculate the International Mission for Prognosis and Analysis of Clinical Trials in Traumatic Brain Injury (IMPACT) prognostic scores and both Marshall and Rotterdam CT scores. Other variables included surgical management, anesthetic, hyperosmotic, and vasopressor agents used, length of mechanical ventilation, the need for tracheostomy, and length of stay. Discharge outcomes included death, withdrawal of life-sustaining therapies, and disposition. The primary clinical outcome was the Glasgow Outcome Scale (GOS) abstracted from the EHR 3–6 months after injury.

MNM reports were collected using a Research Electronic Data Capture (Vanderbilt University, Nashville, TN) electronic data capture tool hosted by UCHealth (17, 18). Each reporting element was discretized into subcomponents describing the central tendencies, trends, events, and correlations for each MNM measurement. Measurements that were not reported were considered missing, whereas measurements not available due to hardware or software limitations were considered reported without subcomponents.

Statistical Analysis

All statistical analyses were carried out using R (version 4.2.2; R Core Team 2021, R Foundation for Statistical Computing, Vienna, Austria) (19). Variables were described using mean ± SD for normally distributed data, median and interquartile range for non-normally distributed data, and proportion for categorical data. A Circos plot was created using the "circlize" package (20) to visualize correlations reported between MNM measurements.

Clinical data were compared between groups using the Student *t* test, Wilcoxon rank-sum test, or chi-square test as appropriate. Physiologic data were compared using the Student *t* test, and effect size was calculated using Cohen's *d*. The proportion of time spent outside of normal thresholds was compared using the Wilcoxon rank-sum test. Tests were considered significant at a p value of less than 0.05 and, for physiologic data, an effect size of greater than 0.20.

We used a multivariable stratified analysis with nonparametric covariable adjustment implemented in the "sanon" package (21). Variable selection was based on known predictors of 6-month clinical outcome: sex, age, initial motor Glasgow Coma Scale (GCS) subscore, pupillary reactivity, and the Rotterdam CT score. Model parameters were reported as odds ratios (OR), 95% CIs, and statistical significance at p value of less than 0.05. A sensitivity analysis was performed to stratify patients and monitor them before and after the establishment of the Neurotrauma Center, as well as updates to joint institutional guidelines.

A statistical process control chart was created to evaluate changes in clinical outcomes over time before and after the implementation of standardized MNM

interpretation and reporting. A split C-chart was generated using the "qicharts2" package (22) to compare the proportion of patients with poor outcomes, defined as GOS 1–3, before and after implementation of standardized MNM interpretation and reporting using Anhoej rules to detect nonrandom variation over time.

RESULTS

Study Population

During the study period, 140 patients with sTBI underwent MNM. Of those, there were six patients with less than 12 hours of monitoring and five patients without neuromonitoring reports. There were 129 patients included for analysis: 45 patients (35%) in the historical control cohort and 84 patients (65%) in the case-cohort who received MNM interpretation and reporting as part of their system of care. The study population averaged 42 ± 18 years old, and 82% were men. There were no significant differences inpatient characteristics between cohorts (**Table 1**).

Injury severity and both Rotterdam and Marshall CT scores were no different between cases and controls. Clinical interventions such as hemicraniectomy and the use of external ventricular drainage (EVD) catheters were similar. In univariate analysis, there were significant differences in the number of times hyperosmotic agents were used per patient (6 [1–8] for controls vs. 3 [1–6] for cases; $p = 0.04$) and in the proportion of hospital days in which anesthetics were used (67% [33–91%] of controls vs. 48% [24–70%] of cases; $p = 0.02$). The length of ICU and hospital stays were similar between cohorts.

MNM Data

The median duration of intracranial MNM was 91 hours [56–125 hr] without a difference in recording duration between cohorts. Table 1 shows the average values of MNM data and the proportion of time spent above established thresholds. A moderate effect size was observed comparing average $ETCO_2$ between controls (32 ± 6 mm Hg) vs. cases (34 ± 6 mm Hg); $p < 0.01$, $d = 0.36$. Patients with standardized MNM interpretation also spent less time above an ICP threshold of 22 mm Hg (22% ± 26%) than historical controls (28% ± 24%; $p = 0.05$).

MNM Reporting Elements

Individual reports based on a standardized template (see **Supplemental Materials**, http://links.lww.com/CCX/B388) uniformly summarized intracranial measurements of pressure, flow, brain oxygenation, and ECOG; systemic measurements of ABP and core temperature; and pupillometry (**Fig. 1**). There were several measures that were unavailable for reporting: CMD was integrated into monitoring during the middle of the case-cohort, and the majority of patients (84%) did not have an EVD. The most common between-physiology correlations were between ICP and CPP (**Fig. 2**).

Clinical Outcome

The overall mortality rate was 48 of 129 (37%), of whom 41 patients underwent withdrawal of life-sustaining therapies. Univariable analysis of the ordinal GOS 3–6 months after injury trended toward better outcomes in the cohort whose management included standardized MNM interpretation and reporting (median GOS 1, IQR [1–3] in controls vs. median GOS 3, IQR [1–4] in cases; $p = 0.06$) (**Fig. 3**).

A multivariable model examining functional outcomes between cohorts was constructed, including sex, age, postresuscitation motor GCS, pupillary examination, and Rotterdam CT scores. Patients with standardized MNM interpretation and reporting had higher odds for better outcomes (OR 1.48; 95% CI, 1.37–1.59) (**Table 2**). Differences in functional outcome over time showed fewer patients had poor outcomes per quarter after the establishment of standardized MNM interpretation and reporting (59%; confidence level bounds 36–82%) relative to the historical control cohort (78%; confidence level bounds 52–100%).

In a sensitivity analysis, patients before and after the establishment of a dedicated Neurotrauma Center were stratified; the parameter estimates of the multivariable model were similar (OR 1.50; 95% CI, 1.40–1.59).

DISCUSSION

We performed a retrospective, historical case-control study that included consecutive patients with sTBI undergoing comprehensive intracranial MNM before and after the implementation of a system of care featuring standardized MNM interpretation and reporting. We found that MNM interpretation and reporting

TABLE 1.
Patient Demographics and Physiologic Data

Variable	All ($n = 129$)	Prereport ($n = 45$)	Reporting ($n = 84$)	p	Cohen's d
Clinical data					
Age (yr); μ (σ)	41.9 (18.0)	42.0 (17.2)	41.8 (18.5)	0.96	NA
Gender (male); n (%)	106 (82.2)	37 (82.2)	69 (82.1)	1.00	NA
Initial post-resuscitation pupillary examination (bilaterally nonreactive); n (%)	19 (14.7)	5 (11.1)	14 (16.7)	0.69	NA
IMPACT linear predictor (unfavorable outcome); μ (σ)	0.44 (0.21)	0.43 (0.21)	0.45 (0.22)	0.69	NA
IMPACT linear predictor (death); μ (σ)	0.25 (0.17)	0.24 (0.18)	0.25 (0.17)	0.74	NA
Rotterdam CT score; median (IQR)	4 (3, 5)	4 (3, 5)	4 (3, 5)	0.77	NA
Marshall CT score; median (IQR)	3 (2, 4)	3 (2, 4)	3 (3, 4)	0.92	NA
Decompressive hemicraniectomy; n (%)	47 (36.4)	17 (37.8)	30 (35.7)	0.97	NA
Delayed hemicraniectomy; n (%)	10 (7.8)	5 (11.1)	5 (6.0)	0.48	NA
External ventricular drainage catheter; n (%)	20 (15.5)	5 (11.1)	15 (17.9)	0.45	NA
Neurodeterioration; n (%)	43 (33.3)	17 (37.8)	26 (31.0)	0.56	NA
Hyperosmotic therapy (number of administrations); median (IQR)	3 (1, 7)	6 (1, 8)	3 (1, 6)	**0.04**	NA
Anesthetics (ICU days, n %); median (IQR)	50 (27.3, 83.3)	66.7 (33.3, 90.9)	47.7 (24.2, 70.4)	0.02	NA
Pressors (ICU days, n %); median (IQR)	22.2 (0.0, 44.4)	13.6 (0.0, 50.0)	25.0 (7.0, 40.0)	0.24	NA
Mechanical ventilation days (ICU days, n %); median (IQR)	10 (6, 15)	9 (6, 15)	11 (6, 16)	0.17	NA
Tracheostomy, n (%)	53 (41.1)	16 (35.6)	37 (44.1)	0.46	NA
ICU LOS (d); μ (σ)	11.7 (6.3)	10.8 (6.3)	12.2 (6.3)	0.23	NA
Hospital LOS (d); μ (σ)	14.5 (8.5)	14.4 (10.8)	14.6 (7.1)	0.95	NA
Died; n (%)	48 (37.2)	20 (44.4)	28 (33.3)	0.29	NA
Withdrawal of life-sustaining therapies; n (%)	41 (31.8)	17 (37.8)	24 (28.6)	0.38	NA
Glasgow Outcome Scale score; median (IQR)	3 (1, 4)	1 (1, 3)	3 (1, 4)	0.06	NA
Physiologic data					
Duration of monitoring (hr); median (IQR)	91.3 (55.8, 125.0)	95.8 (49.4, 125.0)	90.5 (57.6, 124.7)	0.72	NA
Group average physiologic data					
Average mean arterial blood pressure (mm Hg); μ (σ)	89.1 ± 13.4	90.5 ± 13.2	88.3 ± 13.4	< 0.01	0.16
Average $PbtO_2$ (mm Hg); μ (σ)	28.2 ± 20.6	27.2 ± 18.5	28.8 ± 21.7	< 0.01	0.08
Average temperature (C°); μ (σ)	37.5 ± 0.7	37.6 ± 0.8	37.5 ± 0.7	< 0.01	0.14
Average CPP (mm Hg); μ (σ)	73.3 ± 13.7	73.7 ± 14.2	73.1 ± 13.5	< 0.01	0.05
Average End-tidal carbon dioxide concentration (mm Hg); μ (σ)	33.3 ± 6.1	31.7 ± 5.6	33.9 ± 6.1	< 0.01	0.36
Average heart rate (beats/min); μ (σ)	80.1 ± 18.6	79.9 ± 19.0	80.1 ± 18.3	0.09	0.01

(*Continued*)

TABLE 1. (*Continued*)
Patient Demographics and Physiologic Data

Variable	All ($n = 129$)	Prereport ($n = 45$)	Reporting ($n = 84$)	p	Cohen's d
Average ICP (mm Hg); μ (σ)	15.8 ± 8.0	16.5 ± 8.2	15.3 ± 7.9	< 0.01	0.15
Average PRx; μ (σ)	0.17 ± 0.22	0.17 ± 0.22	0.16 ± 0.22	< 0.01	0.05
Average peripheral oxygen saturation (%); μ (σ)	98.9 ± 1.9	98.7 ± 2.1	99.1 ± 1.8	< 0.01	0.17
Abnormal physiologic thresholds					
ICP > 22 mm Hg (recording duration, n %); μ (σ)	23.8 ± 25.3	28.1 ± 23.7	21.5 ± 25.9	0.05	NA
CPP < 60 mm Hg (recording duration, n %); μ (σ)	25.4 ± 23.7	26.1 ± 21.7	25.0 ± 24.8	0.32	NA
PRx > 0.25 (recording duration, n %); μ (σ)	63.0 ± 20.3	63.7 ± 20.3	62.6 ± 20.4	0.79	NA
$Pbto_2$ < 20 mm Hg (recording duration, n %); μ (σ)	47.6 ± 32.3	45.5 ± 29.3	48.7 ± 34.0	0.60	NA

CPP = cerebral perfusion pressure, ICP = intracranial pressure, IMPACT = International Mission for Prognosis and Analysis of Clinical Trials in Traumatic Brain Injury, IQR = interquartile range, LOS = length of stay, NA = not applicable, $Pbto_2$ = partial pressure of brain tissue oxygen, PRx = pressure reactivity index.

was associated with fewer ICP-related interventions and less time spent with elevated ICP, fewer anesthetic days, and differences in average $ETco_2$ during neuromonitoring. After controlling for injury severity, we found that patients for whom daily MNM interpretation and reporting were included as part of their clinical management had 1.5 times the odds for a better outcome compared with a historical cohort of similar patients undergoing MNM without an independent interpretation documented within the EHR.

MNM has been recommended in patients with severe brain injuries to guide clinical management, monitor treatment response, and detect early SBI before permanent neurologic deterioration can occur (1). A recent Delphi statement addressed challenges in the use of MNM, and experts agreed that MNM was important to facilitate individualized management decisions. There was consensus that the use of MNM requires both integration and interpretation of multiple physiologic measurements and recognition of a need to establish a standardized framework for MNM interpretation and reporting (2). However, the amount and complexity of the data generated during the course of MNM is a significant challenge for intensivists and other providers during bedside clinical care (3, 6). The development of standardized terminology used in the interpretation of critical care EEG (13) by a neurophysiologist independent of the critical care team has led to important clinical observations (24) and an impact on clinical care (25). In this study, we report an analogous methodology for implementing standard interpretive reporting of MNM within a system of care to provide clinical teams with information and insights from MNM data.

The use of MNM to guide goal-directed therapies has shown feasibility (26). In one study of MNM in cardiac arrest patients, neuromonitoring improved ABP target attainment (27). In a multicenter clinical trial randomizing patients to an optimum CPP monitoring strategy versus standard care, time spent at optimum CPP was significantly higher in those undergoing monitoring (28). The randomized, controlled Brain Oxygen Optimization in Severe TBI Phase II (BOOST-II) study showed that the targeted use of both ICP and $Pbto_2$ monitoring resulted in nearly four times less brain tissue hypoxia burden (29). Instead of focusing on prespecified targets for intervention, we studied the use of standardized MNM interpretation and reporting in patients for whom an otherwise general set of thresholds was used across both cohorts. We found that patients who received standardized MNM interpretation and reporting spent less time above the recommended threshold of ICP greater than 22 mm Hg (30) relative to patients managed

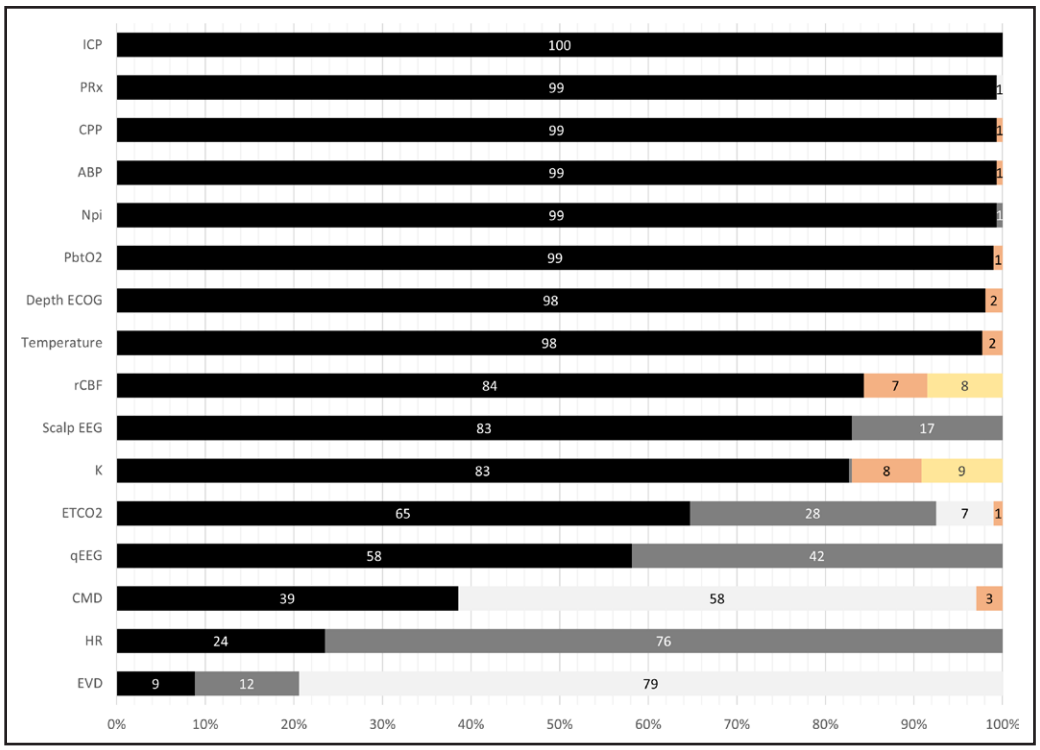

Figure 1. Reported modalities. *Stacked barplot* representing data included within multimodality neuromonitoring reports. Each bar represents one monitoring modality or measurement, and the numbers represent the percentage of all 306 reports with data reported (*black*), with data unavailable for interpretation (*white*), and with data that was not reported (*dark gray*). In some cases, no measurements were reported due to either a device that was nonfunctioning (*orange*) or that could not provide measurements due to technical limitations (*yellow*). ABP = arterial blood pressure, CMD = cerebral microdialysis, CPP = cerebral perfusion pressure, ECoG = electrocorticography, EEG = electroencephalography, $ETco_2$ = end-tidal carbon dioxide concentration, EVD = external ventricular drainage catheter, HR = heart rate, ICP = intracranial pressure, K = thermal conductivity, PRx = pressure reactivity index, NPi = neuropupillary index, $Pbto_2$ = partial pressure of brain tissue oxygen, rCBF = regional cerebral blood flow, qEEG = quantitative EEG.

before implementation. We also found that patients for whom MNM interpretation was provided received fewer hyperosmotic agents during their care. Recently, a standardized approach to MNM interpretation and reporting was implemented in a PICU, resulting in reductions in the duration of ICP monitoring (14). Although our overall MNM duration was similar between groups, this may have been related to the use of additional MNM modalities in our population (16).

Our study provides preliminary evidence that critical care management may be informed by input from MNM interpretation and reporting. We found that the duration of anesthetic use was lower in patients with standardized MNM interpretation. This is similar to another single-center study comparing patients before and after neurocritical care and MNM in sTBI patients in which there was a reduction from an average of 7–5 days of sedation (31). The implementation of MNM interpretation and reporting in pediatric patients also resulted in reduced mechanical ventilation days (14). Although our study found no reduction in mechanical ventilation days, we did observe changes to ventilatory parameters, namely an increase in average $ETco_2$ after the implementation of MNM interpretation and reporting. Recent expert consensus highlighted that the use of MNM is important to abstain from or de-escalate potentially harmful therapies (2). It is conceivable that the interpretation and reporting of MNM information as part of standard care may reassure clinicians about the safety of peeling back anesthetics or avoiding hyperventilation, facilitating spontaneous breathing trials and liberating patients from the ventilator earlier, which could impact hospital costs by promoting efficiency of care.

In a comprehensive review (3), just nine MNM studies were identified that evaluated the impact of MNM in conjunction with targeted interventions on clinical outcomes. Of these, nearly 80% demonstrated a positive impact. However, inconsistencies were noted in the nomenclature for specific SBI patterns. In this study, we relied on summary reports that described the trajectories of and correlation between physiologic measurements without a priori definitions of specific SBI patterns. Standardization of a nomenclature that includes patterns observed during the review and interpretation of MNM may be important to discern or discover clinically relevant physiologic endophenotypes

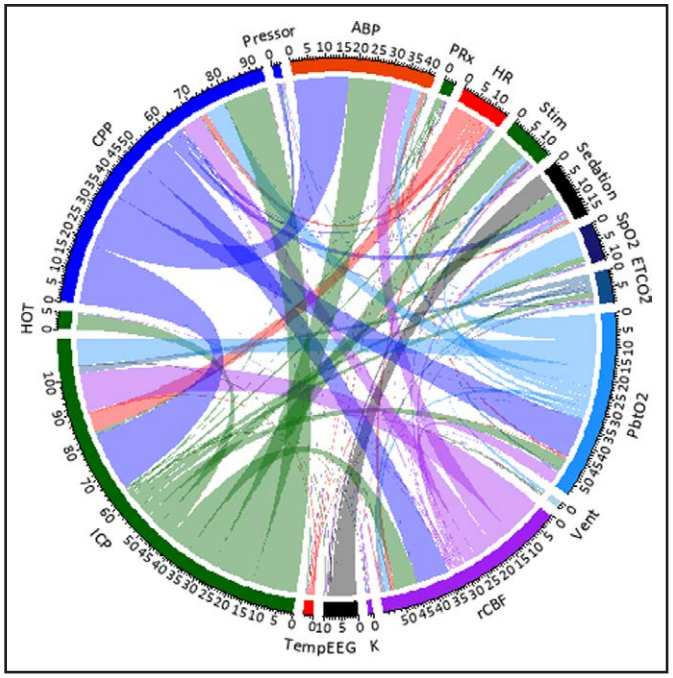

Figure 2. Correlations reported between physiologic data. A *Circos plot* representing correlations reported between physiologic parameters (3). *Circos plots* were designed to visualize genomic data via a *circular layout* in which relationships between pairs of information are represented by *bands* (23) but can be used to visually describe related information in other applications. In this case, the number of correlations described within reports relative to each measurement is represented by the inside track; the size of the bands connecting measurements indicates the number of correlations between two measurements specifically. Correlations were bidirectional, with some bands going to measurements and some coming from measurements. *Colors* represent the origin of the relationship between two physiologic parameters, for example, a *blue band* from cerebral perfusion pressure (CPP) to intracranial pressure (ICP) indicates that when the CPP increased or decreased, there was a change in the ICP appeared to correlate with the change in CPP. ABP = arterial blood pressure, $ETco_2$ = end-tidal carbon dioxide concentration, EEG = electroencephalography, HOT = hyperosmotic therapy, HR = heart rate, $Pbto_2$ = partial pressure of brain tissue oxygen, PRx = pressure reactivity index, rCBF = regional cerebral blood flow, Spo_2 = peripheral oxygen saturation or plethysmography, Stim = stimulation, Temp = core or brain temperature, Vent = ventilator settings.

and to provide the consistency needed to study them (15, 32).

An important caveat to our findings is that the use of diagnostic tools such as MNM in isolation to guide interventions or improve outcomes has been historically fraught (33, 34). MNM-guided interventions are typically targeted to specific physiologic abnormalities measured by one or two monitoring devices, for example, the use of optimum CPP for autoregulatory failure, $Pbto_2$ for brain tissue hypoxia, CMD for metabolic crisis, or ECOG monitoring for spreading depolarizations (26, 35). Although each of these SBI patterns has been associated with mortality or poor functional outcome, their manifestations vary from patient to patient. In contrast, we sought to standardize the review and interpretation of MNM data rather than focus on specific modalities and to provide a written summary for bedside clinicians without mandating specific interventions. This strategy was associated with an improvement in functional outcome and represents the first study to suggest that standardized interpretation and reporting of not only individual diagnostic measurements but also the correlations between them and the patterns of physiologic abnormalities specific to individual patients may help improve outcome independent of injury severity.

This study was limited by its retrospective nature and was conducted exclusively within a single tertiary care center, which may limit generalizability. All MNM data were interpreted and reported by a single clinician, so inter-rater agreement could not be addressed. All clinical decisions were made by the bedside clinical care team, and while our center adheres to a set of local and national management guidelines, we did not quantify clinical decision-making per se as part of this study. National management guidelines evolved during this period with the publication of the newest version of the Brain Trauma Foundation guidelines in 2017 (30). The most relevant change to this study is the recommendation for the use of an ICP threshold of 22 mm Hg, increased from 20 mm Hg in the prior version of the guidelines. In addition, statistical analysis of functional outcomes after severe brain injuries is a challenge in the setting of high rates of mortality and poor outcomes, and to overcome this, we used a multivariable shift analysis, which is advantageous when an intervention may confer relative benefit (36). The mortality rate in our cohort was 37%, which is similar to the overall mortality rates reported from high-income countries (37). However, functional outcome assessments were based on chart review and relied on GOS, which does not capture nuanced functional recovery or

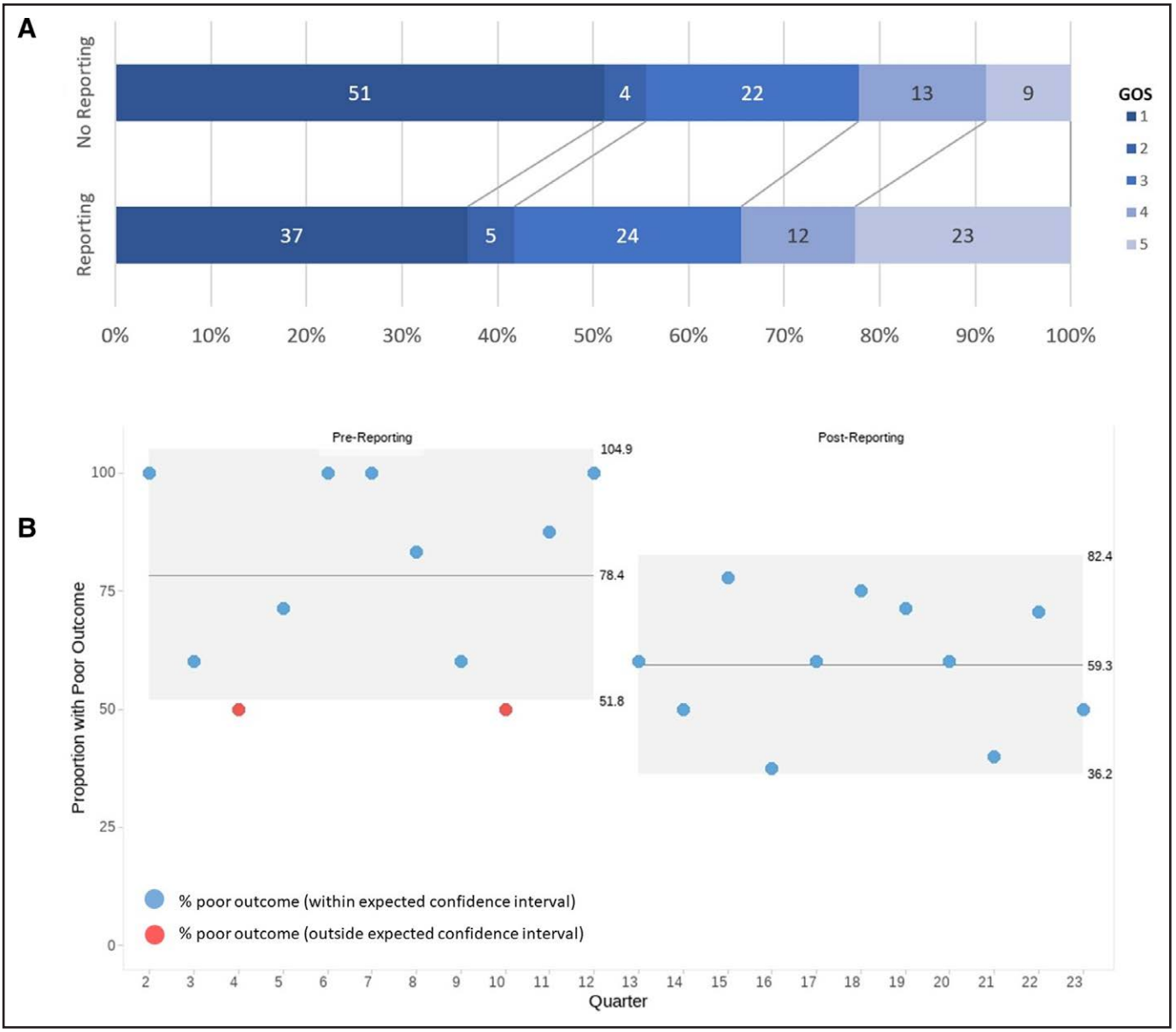

Figure 3. Three- to 6-month functional outcome between cohorts. **A**, *Stacked barplot* comparing Glasgow Outcome Scale (GOS) scores for patients in the historical control cohort vs. patients who received standardized multimodality neuromonitoring interpretation and reporting as part of standard care. Numbers represent the proportion of patients (%) within each category. **B**, Statistical process control chart. The *Y*-axis represents the proportion of patients (%) with poor outcomes, defined as GOS 1–3, during each 3-month quarter (*X*-axis) throughout the duration of the observational study period. The statistical average is represented by the *horizontal dark gray line*, and the calculated upper and lower confidence levels are represented by the *light gray boxes*. Values (%) for each are labeled on the right of each *light gray box* in percentage. Each *dot* (both *red* and *blue*) represents the proportion of patients who experienced poor outcomes. *Blue dots* indicate that the proportion for that quarter was statistically expected based on upper and lower confidence level bounds. *Red dots*, in contrast, indicate that the proportion was outside of the upper and lower confidence levels.

other important domains such as cognition and quality of life.

CONCLUSIONS

In summary, standardized interpretation and reporting of MNM data are a novel and practical approach aimed at offering insights to guide individualized critical care for patients with severe brain injuries. As part of a system of care, this study suggests that independent interpretation of MNM information and communication to clinical care teams through standardized EHR reporting may impact clinical care and improve functional outcomes. However, future research should

TABLE 2.
Multivariable Stratified Analysis

Model	OR (95% CI)	*p*
Reporting ~ sex + age + motor GCS + pupillary examination + Rotterdam CT Score	1.48 (1.37–1.59)	0.0037
Reporting ~ admitted before or after neurotrauma service + sex + age + motor GCS + pupillary examination + Rotterdam CT Score	1.50 (1.40–1.59)	0.0028

GCS = Glasgow Coma Scale score, OR = adjusted odds for improvement in ordinal Glasgow Outcome Scale score.

focus on validating and generalizing standardized approaches to the interpretation of MNM data, quantifying changes in clinical decision-making that result, and prospectively evaluating the impact of standardized MNM interpretation on patient outcomes.

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